AFRL-DE-PS-
TP-2006-1012

AFRL-DE-PS-
TP-2006-1012

SLMS™ Athermal Technology for High Quality Wavefront Control of HEL Tactical Airborne and Relay Mirror Beam Control Applications (Postprint)

Ryan Conk
Bill Goodman

Schafer Corporation
2309 Renard Place SE
Albuquerque, NM 87106

15 July 2005

Conference Proceedings

AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 15 July 2005	**2. REPORT TYPE** Conference Proceedings Postprint	**3. DATES COVERED** *(From - To)* March 05- July 06
4. TITLE AND SUBTITLE SLMS™ Athermal technology for High Quality Wavefront control Of HEL Tactical Airborne and Relay Mirror Beam Control Applications (Postprint)		**5a. CONTRACT NUMBER** FA9451-05-C-0018 **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER** 65502F
6. AUTHOR(S) Ryan Conk*, Bill Goodman		**5d. PROJECT NUMBER** 3005 **5e. TASK NUMBER** DP **5f. WORK UNIT NUMBER** FC
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Schafer Corporation 2309 Renard Place SE Albuquerque, NM 87106		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) *Air Force Research Laboratory 3550 Aberdeen Avenue SE Kirtland AFB, NM 87117-5776		**10. SPONSOR/MONITOR'S ACRONYM(S)** AFRL/DESE **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** AFRL-DE-PS-TP-2006-1012

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release

13. SUPPLEMENTARY NOTES
Author's final manuscript. Published in http://optics.nasa.gov/tech_days/index.html. NASA Marshall Space Flight Center Space Optics Manufacturing Technology Center, Dr. Phil Stahl. GOVERNMENT PURPOSE RIGHTS

14. ABSTRACT
The operational environment for tactical airborne mission is typically on the order of -20 degrees C. Relay mirror systems typically must operate at colder temperatures, on the order of -50 degrees C. The desirable attributes for the mirrors and beam directors for systems operating under these conditions are high quality wavefront control. Wavefront control can be improved through the use of very low absorption coatings which minimize thermal distortion, by using mirrors that do not print-through their lightweighting structures at cryogenic temperatures, by improving the surface figure, surface finish and surface quality of the mirror, by using mirrors with high structural efficiency and excellent damping performance, and by using mirrors that have very high first fundamental frequencies of vibration which will not resonate in response to system disturbances. Since payload weight is an important system driver, lightweighting is also important for the mirrors. In Phase I, Schafer demonstrated a 5 inch dual-band mirror and in Phase II we are demonstrating a 21 inch dual band mirror.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Ryan Conk
Unclassified	Unclassified	Unclassified	SAR	17	**19b. TELEPHONE NUMBER** *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

Schafer
Lightweight Optical Systems (LWOS)
Superior Technology with a System Level Point-of-View©

SLMS™ Athermal Technology for High Quality Wavefront Control of HEL Tactical Airborne and Relay Mirror Beam Control Applications
Phase II SBIR Contract Number FA9451-05-C-0018
Capt. Ryan Conk ~~AFRL/DESE~~ Spell out

AS AMENDED

Dr. Bill Goodman
LWOS Business Lead
Schafer Corporation
2309 Renard Place SE
Albuquerque, NM 87106

505.338.2865

wgoodman@schaferalb.com

Air Force Research Laboratory
Directed Energy Directorate

Mirror Technology Days
August 2005

1

State Title of Brief and Presenter Information

CLEARED
FOR PUBLIC RELEASE
ONLY AS AMENDED
AFRL/DEO-PA
15 JUL 05

AFRL/DE 05-278

Schafer
Lightweight Optical Systems (LWOS)
Superior Technology with a System Level Point-of-View©

Outline

- Program Description
- Dual-Band Coating Performance
- SLMS™ Dual-Band Mirror
- Phase II Project Scope

2

I'll present the program description, discuss dual-band coating performance, show a Silicon Lightweight Mirror Systems (SLMS™) coated mirror that was produced in Phase I, and then summarize the scope of the phase II project which is in-process.

Schafer
Lightweight Optical Systems (LWOS)
Superior Technology with a System Level Point-of-View©

Program Description

- Operational environment for Tactical Airborne missions typically -20 °C
- Operation environment for Relay Mirror Systems typically -50 °C
- Desirable attributes for mirrors/beam directors of these systems are:
  - ⇒ High Quality Wavefront Control
    - → Very Low Absorption (VLA) Coatings for Low Thermal Distortion
    - → Superior Cryogenic Performance Without Print-Through
    - → Super Polishing with Low Cost
    - → High Structural Efficiency (Self Damping)
    - → High First Fundamental Frequency
  - ⇒ Low Weight
- Demonstrate prototype mirrors for the beam control system

3

The operational environment for tactical airborne mission is typically on the order of -20 degrees C. Relay mirror systems typically must operate at colder temperatures, on the order of -50 degrees C. The desirable attributes for the mirrors and beam directors for systems operating under these conditions are high quality wavefront control. Wavefront control can be improved through the use of very low absorption coatings which minimize thermal distortion, by using mirrors that do not print-through their lightweighting structures at cryogenic temperatures, by improving the surface figure, surface finish and surface quality of the mirror, by using mirrors with high structural efficiency and excellent damping performance, and by using mirrors that have very high first fundamental frequencies of vibration which will not resonate in response to system disturbances. Since payload weight is an important system driver, lightweighting is also important for the mirrors. In Phase I Schafer demonstrated a 5 inch dual-band mirror and in Phase II we are demonstrating a 21 inch dual band mirror

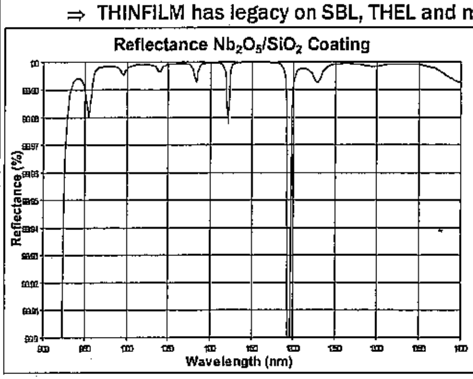
Schafer

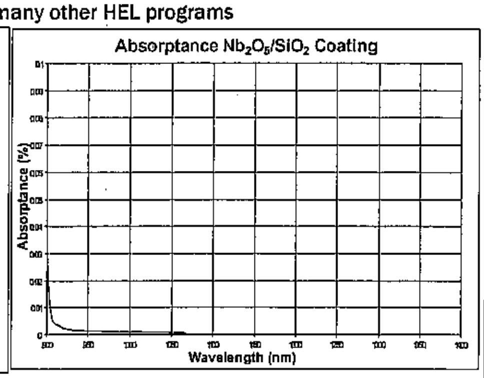
Lightweight Optical Systems (LWOS)

Superior Technology with a System Level Point-of-View©

Dual-Band Very Low Absorption (VLA) Coating Design (1 of 4)

- >99.999% reflectivity @ 1.064μm and 1.315μm @ normal angle of incidence
- 27 Pairs of Nb_2O_5/SiO_2 (high/low index of refraction) stack
  - ⇒ 13.35 microns total thickness
  - ⇒ Demonstrated low absorption, low scatter and high damage resistance at wavelengths of interest
- Wavelength dependent refractive index and extinction coefficient data from Schafer THINFILM code
  - ⇒ THINFILM has legacy on SBL, THEL and many other HEL programs





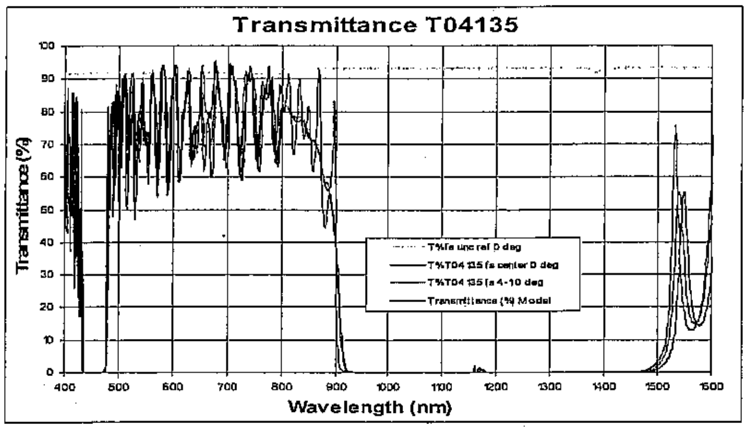
4

In Phase I Schafer designed a coating targeted at better than 99.999% reflectivity at 1064 and 1320 nm. The normal angle of incidence coating had 27 layer pairs of high index niobia and low index silica. The total thickness of the all dielectric stack was a little more than 13 microns. These materials have demonstrated low absorption, low scatter and high damage resistance at the wavelengths of interest. The dispersion data for the materials are part of Schafer's proprietary THINFILM code. THINFILM was used to design coatings for the SBL and THEL programs as well as many other HEL applications. The plots show that a very low absorption coating design was achieved.

Schafer
Lightweight Optical Systems (LWOS)
Superior Technology with a System Level Point-of-View©

Dual-Band Very Low Absorption (VLA) Coating Design (2 of 4)

- Transmission measured using Cary 5 spectrophotometer (all normal incidence)
  - ⇒ Uncoated fused silica reference sample
  - ⇒ Coated fused silica witness sample at center of coating tool
  - ⇒ Coated fused silica witness sample 4 inches from center of tool
- Theoretical design plotted for comparison
  - ⇒ Spectrophotometer lacks good resolution over 800-900 nm bandwidth



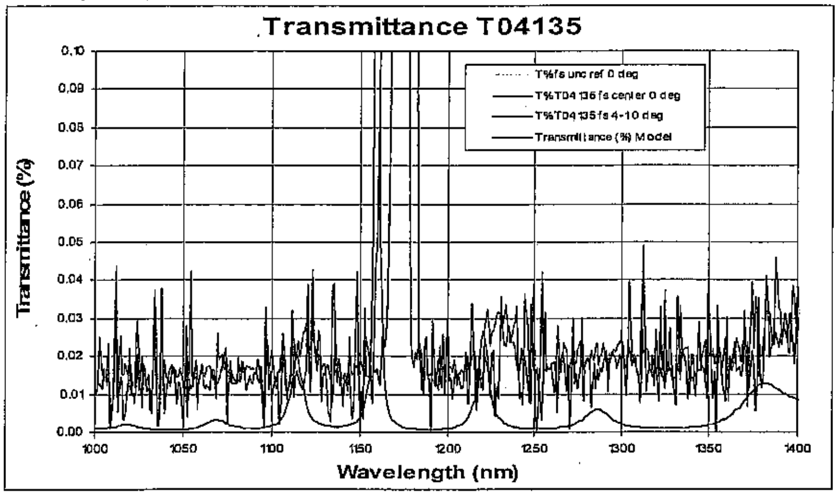
5

The designed coating was deposited on fused silica and the transmission of the film was compared with an uncoated fused silica witness sample...coated samples were obtained from the center and edge of the coating chamber. The graph shows excellent agreement between the prediction and the coated samples with the exception of the 800-900 nm bandwidth, which was known to be a region of poor resolution for the spectrophotometer.

Schafer
Lightweight Optical Systems (LWOS)
Superior Technology with a System Level Point-of-View©

Dual-Band Very Low Absorption (VLA) Coating Design (3 of 4)

- Design and deposited coating agree to within 0.01-0.02%
- Sum of Reflected and Absorptance is 99.99%
- Measured transmittance over wavelengths of interest are in the noise floor of the spectrophotometer



6

Blowing up the waveband of interest we see that the as-deposited coating is within 0.01-0.02% transmission of the predicted performance. The sum of reflectance and absorptance for the as-deposited coating is 99.99%. The transmittance plot shows that the measurement is at the floor of the resolution capability of the spectrophotometer. One would have to perform laser absorption calorimetry to verify a coating with better performance.

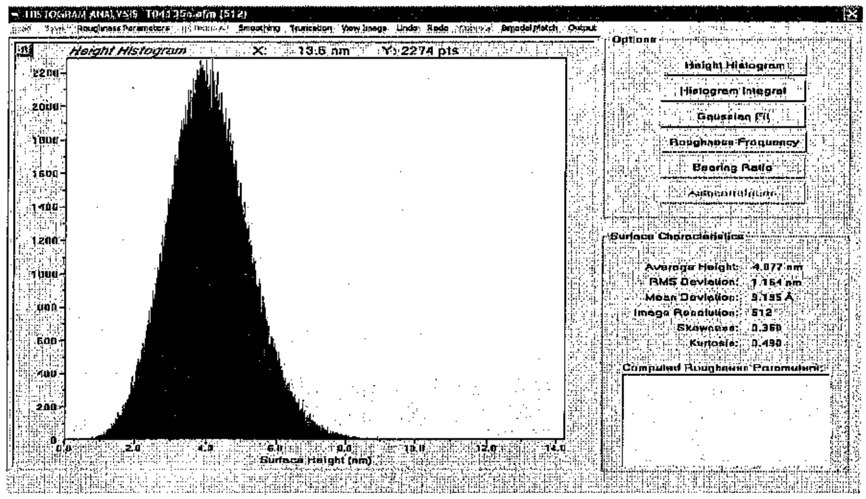
Schafer

Lightweight Optical Systems (LWOS)

Superior Technology with a System Level Point-of-View©

Dual-Band Very Low Absorption (VLA) Coating Design (4 of 4)

- Surface roughness distribution measured with Atomic Force Microscope
- Average roughness is 4 ± 1 nm – very smooth for a coating of this thickness
- BRDF measured at 890 parts per million



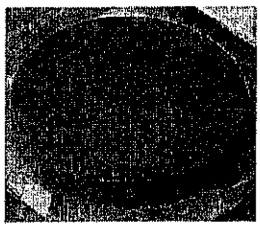
7

An atomic force microscope was used to measure the roughness of the as-deposited coating. Although the coating is very thick, its roughness is excellent with a value of 4 nm. The BRDF for the coating is also low having measured at 890 parts per million.

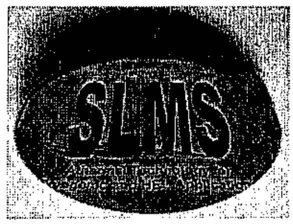
Schafer
Lightweight Optical Systems (LWOS)
Superior Technology with a System Level Point-of-View©

SLMS™ Dual-Band Mirror

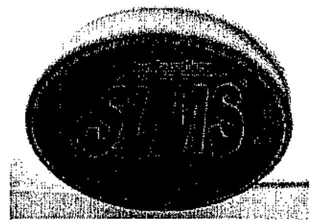
- 5-inch by 0.7 inch, 9.7 kg/m^{2}areal density, 3.5 kHz 1st fundamental frequency
- Figure accuracy <λHeNe /10 PV, and a surface roughness of <10 Å RMS



Substrate



Polished Substrate



Coated Mirror

8

This coating was deposited on a 5 inch diameter plan SLMS™ mirror. The areal density of the first fundamental frequency of the SLMS™ better than one would obtain with a light weighted beryllium mirror of the same weight. The SLMS™ had an excellent surface figure and finish.

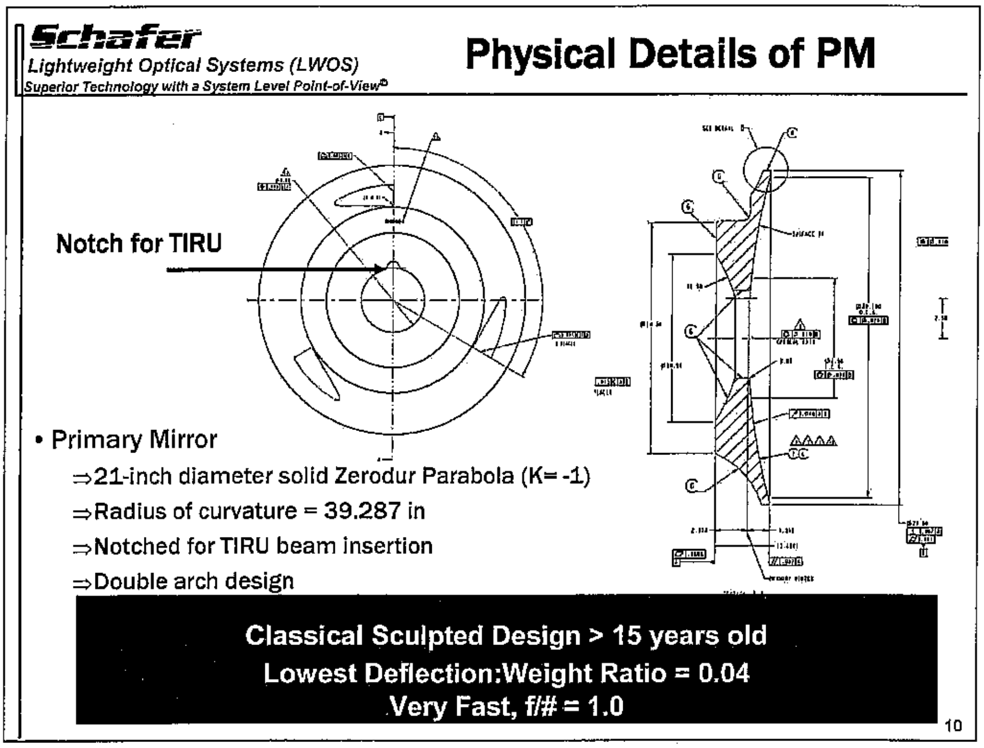
Schafer
Lightweight Optical Systems (LWOS)
Superior Technology with a System Level Point-of-View©

Phase II Project

- Design and Fabricate SLMS™ Beam Director Primary Mirror
  - ⇒ 50 cm Clear Aperture
  - ⇒ F/# = 1.00
  - ⇒ K = -1 (Parabola)
  - ⇒ Customer specified NIR laser coating
- Design and Fabricate Athermal Mirror Mount for Simulating and Testing in Relevant Operational Environment (proprietary)

9

In Phase II Schafer will be producing a primary mirror with a clear aperture of 50 cm and an F/1. The lightweight, high stiffness mirror will be coated with a near IR coating as specified by the customer. A custom designed mount is being produced in order to perform simulated environmental testing of the mirror at NASA MSFC.



The customer provided a notional primary design as a point design for comparison with Schafer's SLMS™ technology. This design is a classical double-arch configuration that minimizes deflection to weight ratio. It is also a very heavy mirror as will be seen.

Schafer
Lightweight Optical Systems (LWOS)
Superior Technology with a System Level Point-of-View©

Basic Primary Mirror Specs

- Clear Aperture Diameter: 50 cm
- f/#: 1.0
- As-Polished Wavefront Error (residual surface error w/ tilt & focus removed): 0.0169 waves rms @ 1.315 um (0.035 waves rms HeNe)
- Weight: 46 lbs **(Areal Density of 93.57 kg/m^2)**
- Coating Spec:
  - ⇒ Reflectivity:
    - → 1.315 -1.319 um: 0.9992
    - → 1.06 - 1.08 um: 0.9900
    - → 0.633 um: 0.9000
    - → 0.91 um: 0.9900
  - ⇒ Absorption: <200 ppm
  - ⇒ Scatter: <300 ppm
  - ⇒ Damage Threshold: >20 kW/cm^2
  - ⇒ VLA Coating Provides Relatively No Thermal Distortion

Figure Requirement Well Within Capability for SLMS™
Classical Zerodur Double Arch Design is Very Heavy
Coating Performance is Very Reasonable

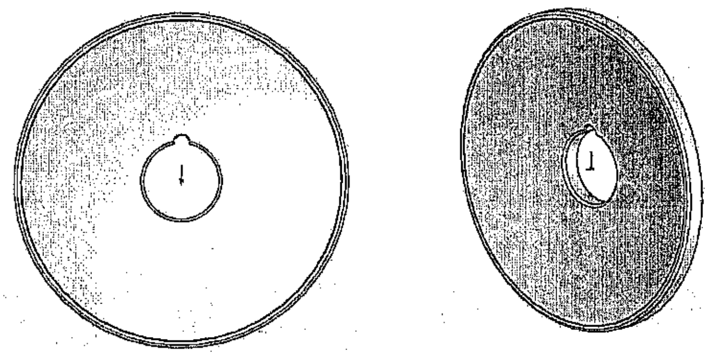
11

The basic mirror specifications for the customer supplied design are summarized as follows…a clear aperture of 50 cm, and f number of 1, a surface error with tilt and focus removed of 0.035 waves at HeNe, a weight of 46 pounds (this is a very high 94 kg/square meter). The coating requirements include both visible and Near infrared performance. It is of course desired that the mirror coating be low absorption so as to minimize thermal distortion. All of the requirements are well within Schafer's current demonstrated capabilities.

Schafer
Lightweight Optical Systems (LWOS)
Superior Technology with a System Level Point-of-View®

SLMS™ Primary Mirror

- Schafer Mirror Requirements Captured in an ISO9001:2000 Drawing
- Mirror will weigh 7. 1 pounds (3.23 kg)



12

Schafer's design is a meniscus mirror that weighs only 7.1 pounds.

Schafer

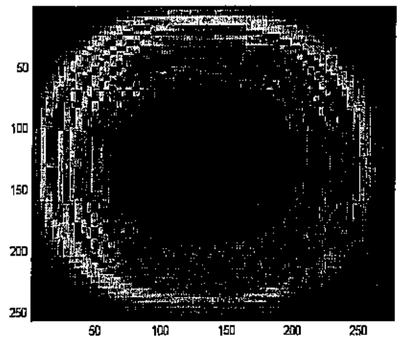
Lightweight Optical Systems (LWOS)

Superior Technology with a System Level Point-of-View©

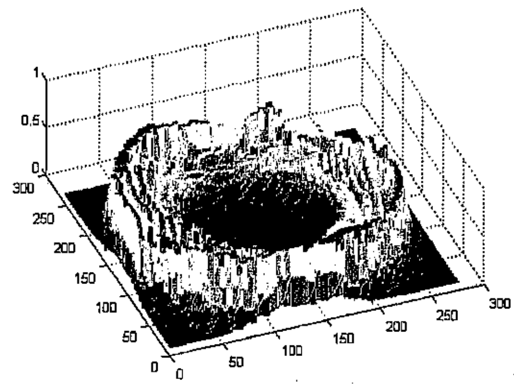
Intensity Distribution

Map as shown in presentation:

"Primary Mirror Specifications for AFRL"



Schafer Processed the 2-D Intensity Plot and Generated a Normalized 3-D Intensity Map



13

Schafer will map the customer supplied notional intensity distribution onto the mirror finite element model in order to perform thermal distortion analysis.

Schafer
Lightweight Optical Systems (LWOS)
Superior Technology with a System Level Point-of-View©

Benefits to AFRL Program

- SLMS™ Primary Mirror is ~7.1 lbs vs 46 lbs for Zerodur, Requirements Can be Relaxed for Gimbal and Motors
  - ⇒ Lighter Mirror Mounts, Structure and Counterweights Can Be Employed
- Primary Mirror First Fundamental Frequency of ~760 Hz
  - ⇒ Increased Stiffness and High Damping Allows Reduced Ringdown Time and Jitter During Slew, Improves Beam Director Line of Sight
- f/# = 1.0 Will be the "Fastest" SLMS™ Ever Produced
  - ⇒ Small f/# Optics Are Required for Compactness in Numerous Optical System
  - ⇒ Faster Mirrors Result in Lower Inertial Loads on Gimbals (Shorter Telescope)
- SLMS™ Shown to Have Better Dimensional Stability Than Zerodur
  - ⇒ High Conductivity SLMS™ Does Not Irradiance Map
  - ⇒ Foam Provides A Well Supported Facesheet (No Quilting)
  - ⇒ High Stiffness, High Thermal Diffusivity SLMS™ Does Not Print-Through at Cryo
- SLMS™ Compatible With VLA Coating Technology
  - ⇒ Legacy VLA Coatings for HELs Were Developed on Single Crystal Silicon

SLMS™ Are A Breakthrough Technology For Tactical Airborne Beam Control Applications

14

There are numerous benefits of SLMS™ technology for the Air Force mission…these include a dramatic reduction in weight, which in term will spawn secondary weight savings for the mirror mounts, telescope structure and counterweights and thus the gimbals and motors. The SLMS™ has a predicted first fundamental frequency of 760 Hz meaning that the ringdown time and jitter of the mirror during slew maneuvers will be greatly reduced, the ability to produce very fast optical prescriptions means that shorter telescopes can be used and this favors lower inertial loading, SLMS™ dimensional stability has been demonstrated in the laboratory under laser loading and the performance has exceeded that of Zerodur…SLMS™ do not irradiance map under laser loading, nor show print-through at cryogenic temperatures. Finally SLMS™ can be coated with anything that single crystal silicon of glass mirrors can.

Thus SLMS™ Technology is a breakthrough for tactical airborne and relay mirror system beam control applications.

Schafer
Lightweight Optical Systems (LWOS)
Superior Technology with a System Level Point-of-View©

Summary

SLMS™ in Conjunction with VLA coating technology offers Dramatic Improvement for Tactical Airborne and Relay Mirror Systems

High Quality Wavefront Control
Low Polishing Cost
Very Low Absorption (VLA) Coatings for Low Thermal Distortion
Superior Cryogenic Performance for No Print-Through
High Structural Efficiency
High First Frequency

15

SLMS™ in Conjunction with VLA coating technology offers Dramatic Improvement for Tactical Airborne and Relay Mirror Systems

- **High Quality Wavefront Control**
    - **Low Polishing Cost**
    - **Very Low Absorption (VLA) Coatings for Low Thermal Distortion**
    - **Superior Cryogenic Performance for No Print-Through**
- **High Structural Efficiency**
    - **High First Frequency**
    - **Lower Weight**